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The Sensory Striatum

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The dorsal striatum is regarded as a substrate for action selection and motor habits, but much of it is connected to sensory, not motor, cortex. In this issue of *Neuron*, Reig and Silberberg (2014) use intracellular recording to reveal connections between sensory cortex and striatum.

Two people are having a conversation across a crowded room, and I can't make out what they are saying. One of them glances my way. Are they discussing my high taste in clothing, or are they plotting to kill me? Perhaps the glance was meaningless and I do not figure into their conversation at all. There is not enough evidence to make an informed decision. Without thinking I apply a policy based on my previous experience with things of this sort.

At this level, perceptions are like actions. The available sensory data leave the problem underdetermined. One must be selected from a list of candidates, and the selection is best made from both a priori likelihood and the potential cost and benefit of each choice. Most of these perceptual selections do not break the surface of our consciousness. They are perceptual habits built from prior success and failure. Like bad motor habits, bad perceptual habits can lead to trouble.

Motor habits and action selection are often associated with the basal ganglia, and especially the striatum (Smith and Graybiel, 2014). Dopaminergic reinforcement-related signals modify synaptic transmission in the corticostriatal pathway, and this may implement the formation of habitual motor choices. Striatal neurons often fire in relation to movement in a way that is consistent with this action selection hypothesis (Jin et al., 2014). The striatal literature on motor action selection is derived mainly from studies of one region in the striatum, the region that receives inputs from cortical motor areas. The motor and premotor cortices project heavily to the striatum, but not to all of it. There are large areas in the striatum that receive no projections at all from the motor areas.

Cortical projections to the striatum obey a rough topographical organization. Each cortical region has a corresponding striatal recipient zone (e.g., Gerfen and Wilson, 1996), but projections from different cortical areas overlap. The patterns of overlap have attracted much experimental work, with the outcome that functionally related cortical regions have overlapping projections in the striatum. For example, there are multiple cortical somatosensory representations of the fingers, but their projections are largely overlapping in the striatum. In the striatum there may be only a single somatosensory representation of the fingers (Flaherty and Graybiel, 1991).

Despite its reputation as a motor structure, there have been many studies of striatal sensory responses. The first microelectrode studies of the basal ganglia focused on sensory properties of striatal neurons (Albe-Fessard et al., 1960). There have been multiple subsequent studies, all showing that some striatal neurons respond to sensory stimuli, even in anesthetized or immobilized animals incapable of movement (e.g., Mowery et al., 2011; Pidoux et al., 2011; Schneider and Lidsky, 1981). The cells sometimes respond to multiple sensory modalities. It is assumed that the sensory responses of striatal neurons derive from their cortical projections. Certainly, the functions of cortical regions and their striatal recipient zones are closely aligned. In their classic study, Divac et al. (1967) made lesions in specific nonmotor cortical areas or in their striatal recipient zones, and showed that these produced similar deficits. For example, lesions in the inferior temporal cortex produced deficits in visual recognition learning that were similar to those produced by lesions in its recipient zone in the tail of the caudate. But intralaminar thalamic neurons also respond to sensory stimuli (Fisher and Reynolds, 2014), and they contribute a powerful excitatory input the striatum. The sensory responses of striatal neurons are strikingly different from those of most neurons in the primary sensory cortices, suggesting that they may be influenced from elsewhere. On the other hand, striatal projections arise from a small subset of cortical neurons whose sensory responses have not been characterized either. Do the sensory responses of striatal neurons derive directly from their cortical inputs?

In the paper by Reig and Silberberg (2014), strong evidence is presented for a cortical origin of the sensory responses of striatal neurons. Identified striatal neurons were recorded specifically in somatosensory or visual cortex recipient zones, identified by axonal tracing. Responses to somatosensory or visual stimuli were restricted to the striatal region receiving inputs from those two cortical regions. Response magnitudes were stronger in the center of the cortical projection zone than at the edges. Somatosensory and visual recipient zones in the striatum are partly overlapping, and in the overlap region there were striatal cells responding to both modalities. The sensory responses of striatal projection neurons had the characteristic features described in previous studies, including sequential excitatory and inhibitory components, encouraging generalization of the results to other species and other anesthetic and recording conditions used in previous studies.

Response latencies also suggest a cortical origin of the responses. EPSP latencies are independent of response amplitude and are a direct measure of conduction time. The latencies of sensory responses of striatal neurons can be

compared to those in the primary somatosensory cortex. If the sensory input to the striatum originates in the cortex, its timing should be predictable from the pathway conduction times. The comparisons can be made bilaterally in both the cortex and striatum. If an air puff is delivered to the whiskers unilaterally, the response in the contralateral cortex is primary, having been transmitted through the thalamus on that side. The response ipsilateral to the air puff is secondary to activation in the contralateral cortex. The ipsilateral cortical response comes via the axon of callosal neurons on the contralateral side.

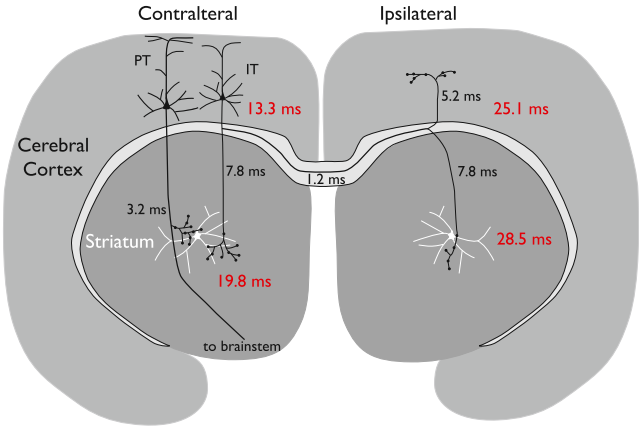

Figure 1. Corticostriatal Pathways and Their Latencies from the Rat, and Mouse Somatosensory Mean Latencies

Corticostriatal pathways and their latencies from the rat (in black), and mouse somatosensory mean latencies (in red), from Reig and Silberberg (2014).

The callosal neurons comprise one of the classes of cortical pyramidal cells that innervate the striatum, and they often innervate the striatum bilaterally (Wilson, 1987). These cells belong to a larger class of cells called IT-type (intratelencephalic) neurons, meaning their axons do not innervate brain stem or spinal structures. The neurons that do send their axons to the brainstem and/or spinal cord are called PT-type neurons (it is confusing, but neurons whose axons form the pyramidal tract are only a subset of PT-type pyramidal cells). PT-type cells never have callosal axonal branches and do not innervate structures in the forebrain on the opposite side. This arrangement is shown in Figure 1. Whisker sensory information enters the cortex on the side contralateral to the stimulus. There both groups of cortical pyramidal cells could contribute to the EPSP in striatal neurons. On the ipsilateral side, cortical EPSPs should be delayed by the callosal conduction time. The ipsilateral striatal response, if it arises from branches of the same callosal axons, could arrive at nearly the same time. If it required synaptic excitation of the ipsilateral cortex, it would be delayed several more milliseconds.

Conduction times of these pathways in mice have not been reported, but conduction times are often conserved across species. For example, the latency in the mouse contralateral striatum in the Reig and Silberberg paper (Reig and Silberberg, 2014) (19.8 ms) is close to that reported for rats (21.0 ms; Pidoux et al., 2011), despite the large difference in conduction distances. Perhaps preservation of the timing of signals in the cortex and striatum is important for their function, because axon conduction velocities are scaled to keep the timing constant despite large differences in brain and body size. For example, the mean latency of striatal intracellular responses to contralateral forepaw stimulation in the cat (20 ms) is almost identical to the latency for mouse whisker stimulation (Wilson et al., 1983). In Figure 1, the latencies reported by Reig and Silberberg are compared to the average axon conduction times measured using direct stimulation of the pathways in the rat (Wilson, 1987, 1995).

The delay from cortex to the striatum on the contralateral side closely corresponds to the conduction time for the axons of the slower IT-type neurons, especially allowing 1–2 ms for the shortest integration time required for generating action potentials in the cortical neurons. This suggests that the contralateral striatal response is dominated by the IT-type cell. On the ipsilateral side, both cortical and striatal responses are consistent with the conduction times of callosal IT-type neurons, although both are several milliseconds later than is expected from this most direct pathway. Possibly, some neurons recorded by Reig and Silberberg (2014) in the ipsilateral cortex and striatum were activated by polysynaptic circuits on the ipsilateral side. Some neurons in the ipsilateral cortex, firing in response to callosal excitation, might activate neurons in the striatum, and this might account for the longer delay.

Striatal projection neurons also fall into two classes, based on their axonal targets and expression of dopamine receptors. One class of neurons, projecting solely to the globus pallidus (called indirect pathway neurons) express D2 dopamine receptors. The others (direct pathway neurons) project to both the globus pallidus and substantia nigra and express D1 receptors. Reig and Silberberg (2014) identified striatal neurons of these two classes and compared their latencies to somatosensory stimulation. On the contralateral side these neurons had similar latencies, indicating that they receive inputs from cortical neurons with the same conduction velocities. On the ipsilateral side direct pathway neurons responded on average 6 ms later than the indirect pathway. The indirect pathway neurons' latencies correspond roughly to those predicted by a direct connection from contralateral IT-type neurons (as in Figure 1), but the direct pathway neurons had an average latency much later than predicted. These observations suggest no difference in the cortical pathway to direct and indirect pathway neurons on the contralateral side, but it is possible that the direct pathway neurons' response on the ipsilateral side was via a polysynaptic route.

All the cortical sensory and associational areas have projection fields in the striatum, and they overlap in patterns that often do not include a motor component. The segregation of motor and nonmotor regions of the dorsal striatum is preserved in the striatal outflow to the output nuclei of the basal ganglia, thalamic connections, and cortical targets (Middleton and Strick, 2002). Most of what we know about the function of the striatum is confined to one part of it, the motor part. The rest of the striatum may have as

diverse an array of functions as the cerebral cortex itself.

REFERENCES

Albe-Fessard, D., Rocha-Miranda, C., and Oswaldo-Cruz, E. (1960). Electroencephalogr. Clin. Neurophysiol. *12*, 649–661.

Divac, I., Rosvold, H.E., and Szwarcbart, M.K. (1967). J. Comp. Physiol. Psychol. *63*, 184–190.

Fisher, S.D., and Reynolds, J.N.J. (2014). Front. Behav. Neurosci. *8*, 115.

Flaherty, A.W., and Graybiel, A.M. (1991). J. Neurophysiol. *66*, 1249–1263.

Gerfen, C.R., and Wilson, C.J. (1996). In Handbook of Chemical Neuroanatomy, *Volume 12*, L.W. Sqanson, A. Björklund, and T. Hökfelt, eds. (Amsterdam: Elsevier Press), pp. 371–468.

Jin, X., Tecuapetla, F., and Costa, R.M. (2014). Nat. Neurosci. *17*, 423–430.

Middleton, F.A., and Strick, P.L. (2002). Cereb. Cortex *12*, 926–935.

Mowery, T.M., Harrold, J.B., and Alloway, K.D. (2011). J. Neurophysiol. *105*, 2225–2238.

Pidoux, M., Mahon, S., Deniau, J.-M., and Charpier, S. (2011). J. Physiol. *589*, 263–281.

Reig, R., and Silberberg, G. (2014). Neuron *83*, this issue, 1200–1212.

Schneider, J.S., and Lidsky, T.I. (1981). J. Neurophysiol. *45*, 841–851.

Smith, K.S., and Graybiel, A.M. (2014). Front. Behav. Neurosci. *8*, 39.

Wilson, C.J. (1987). J. Comp. Neurol. *263*, 567–580.

Wilson, C.J. (1995). In Functions of the Cortico-Basal Ganglia Loop, M. Kimura and A.M. Graybiel, eds. (Tokyo: Springer-Verlag), pp. 50–72.

Wilson, J.S., Hull, C.D., and Buchwald, N.A. (1983). Brain Res. *270*, 197–208.